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PCE groundwater quality assessment of the University of Northern Iowa campus area

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This research paper presents the findings of an effort to better characterize the spatial, temporal, and transport attributes of a PCE groundwater plume that exists within the Devonian aquifer underlying the University of Northern Iowa campus and the surrounding area in Cedar Falls, Iowa. Findings reveal the plume underlies the eastern portion of UNI's campus, is hydraulically influenced by the operation of UNI's cooling-water wells, and trace amounts of PCE are found in cooling water discharged into the Southwest branch of Dry Run Creek by UNI. Findings also indicate the direction of groundwater flow within the study area is quite different from flow directions estimated in a United States Geological Survey (2002) study. Furthermore, the operation of UNI's well field provides a degree of hydraulic protection for a nearby municipal drinking water well. Finally, one former drycleaning operation is implicated as the most probable known point source because of its spatial position relative to groundwater flow and aquifer susceptibility.

PCE GROUNDWATER QUALITY ASSESSMENT

OF THE

UNIVERSITY OF NORTHERN IOWA CAMPUS AREA

A Research Paper Submitted in
Partial Fulfillment of the Requirements for the Degree:

Master of Arts - Geography

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Abstract

Perchloroethylene (PCE), is a colorless, nonflammable, and relatively insoluble chlorinated solvent once widely used for dry cleaning and metal degreasing operations. Because of its past widespread use, poor solvent management practices, and environmental persistence, PCE is a common contaminant found in groundwater supplies. Potential health concerns include liver problems and increased cancer risk.

This research paper presents the findings of an effort to better characterize the spatial, temporal, and transport attributes of a PCE groundwater plume that exists within the Devonian aquifer underlying the University of Northern Iowa campus and the surrounding area in Cedar Falls, Iowa. Findings reveal the plume underlies the eastern portion of UNI's campus, is hydraulically influenced by the operation of UNI's cooling-water wells, and trace amounts of PCE are found in cooling water discharged into the Southwest branch of Dry Run Creek by UNI. Findings also indicate the direction of groundwater flow within the study area is quite different from flow directions estimated in a United States Geological Survey (2002) study. Furthermore, the operation of UNI's well field provides a degree of hydraulic protection for a nearby municipal drinking water well. Finally, one former dry-cleaning operation is implicated as the most probable known point source because of its spatial position relative to groundwater flow and aquifer susceptibility.

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INTRODUCTION

Tetrachloroethylene, also known as perchloroethylene (PCE), is a colorless, nonflammable, and relatively insoluble chlorinated solvent once widely used for dry cleaning and metal degreasing operations (US EPA, 2011a). Because of high usage rates, especially in dry cleaning businesses, and poor solvent storage, handling, and disposal practices, PCE releases into the environment were more common in the past (Linn and others, 2010). Past dry cleaning operations were frequently prone to equipment leaks, transfer or equipment spills, storage problems, and ground discharges (Mohr and others, 2007). Additionally, before environmental regulations were in place (the first Resource Conservation and Recovery Act regulations were published in 1980), waste PCE and PCE-laden wastewater were often disposed to leaky sanitary sewer or septic systems (US EPA, 2011b; Mohr and others, 2007; Linn and others, 2010).

Because it is relatively insoluble and has a specific gravity greater than water (1.62 g/cm^3), PCE is a dense, non-aqueous phase liquid (DNAPL). These characteristics allow PCE to reach deep aquifers, particularly in areas where confining layers are thin or absent and downward hydraulic gradients are present. Although relatively insoluble in water, dissolved PCE is quite mobile and persistent in the subsurface environment. Consequent to past widespread use and poor solvent management practices, PCE is commonly detected in groundwater supplies; plumes may extend over a mile from the source (Mohr and others, 2007; Linn and others, 2010). Potential health effects related to liver problems and increased cancer risk resulted in the US EPA establishing a maximum contaminant level (MCL) of 5 parts-per-billion (ppb) for PCE in drinking water supplies (US EPA, 2011c).

Local PCE Occurrence in Groundwater

Groundwater in the Cedar Falls, Iowa area shares the legacy of past PCE usage and poor management practices. Historic groundwater sampling results for a municipal (Cedar Falls) drinking-water well and recent sampling results for a cooling-water well operated by the University of Northern Iowa (UNI) indicate PCE is present in the Devonian carbonate aquifer underlying the area. UNI and the city of Cedar Falls rely heavily upon this highly productive aquifer for campus building cooling needs and as a municipal water supply, respectively. UNI withdraws approximately 3.7 billion gallons of groundwater from the aquifer annually, largely for its seasonal once-through campus building cooling needs (Gedlinske, 2010a). Cedar Falls operates eight wells ranging in depth from 147 to 275 feet to mine the aquifer's high-quality groundwater. In 2010, approximately 1.48 billion gallons of water were pumped from the Devonian aquifer for municipal purposes (CFU, 2011).

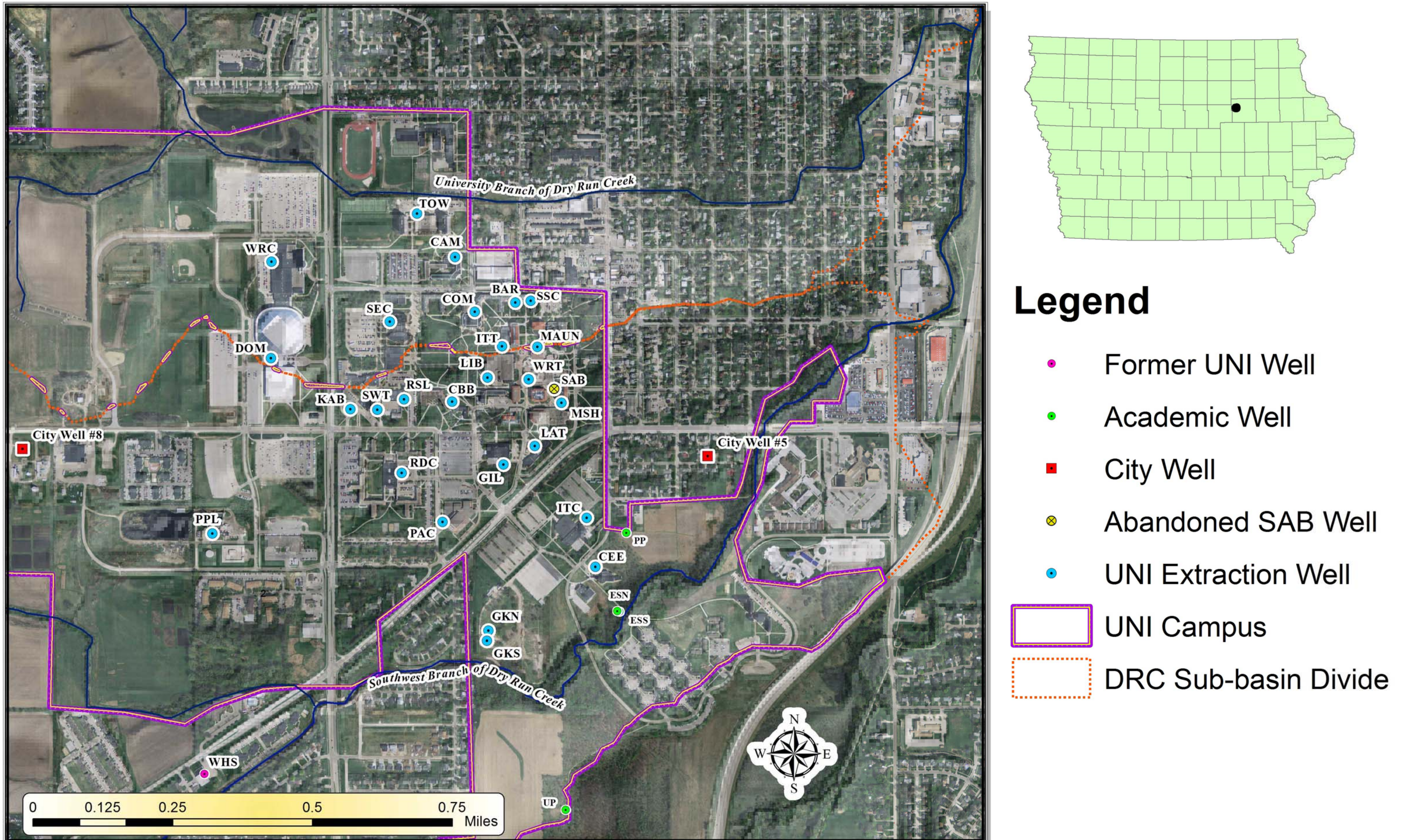
Study Site and Objectives

The primary intent of this study is to gain a more complete understanding of the spatial and temporal characteristics of the PCE groundwater plume that exists within the Devonian aquifer underlying UNI's campus and adjacent area. Consequently, the study area was selected based on the spatial distribution of UNI's well field and the location of City Well #5, a municipal well with a history of PCE detections (Figure 1). It is roughly 2.6 square miles in area.

Research questions addressed by this study include the following:

- What does a more extensive groundwater sampling effort reveal about the spatial extent of the PCE plume?

Figure 1 - PCE Study Area



- How does the spatial distribution of the PCE plume compare to nearby potential point sources, areas where the Devonian aquifer is more susceptible to surface contamination, and estimated direction of groundwater flow?
- How does UNI's seasonal groundwater use affect plume movement and the temporal detection of PCE in the nearby municipal well (City Well #5)?
- With respect to PCE, to what degree does cooling-water discharged from UNI affect the surface water quality of Dry Run Creek?

PREVIOUS STUDIES

The following is a synopsis of previous work performed in the area relevant to the objectives of this study.

UNI Groundwater Use Study

In 2010, Gedlinske (2010a) completed a study on UNI's groundwater use from the Devonian aquifer. This review included: GPS mapping of active and former UNI well locations used to extract cooling-water from the aquifer; GPS mapping of UNI academic and research area well locations; a compilation of well construction details; GPS mapping of discharge points into Dry Run Creek conveying noncontact cooling-water (i.e., water used for cooling which does not come into direct contact with any raw material, product, byproduct, or waste); a review of the area's stratigraphy, hydrogeology, and historic groundwater levels based on information obtained through drilling logs and UNI records; quantification and temporal characterization of UNI's annual groundwater use; and identification of interrelationships between groundwater extraction and the surface water hydrology of Dry Run Creek.

An historical review of the Southwest branch of Dry Run Creek was also completed by Gedlinske (2010b). The study relied on historical documents to identify significant, but forgotten, characteristics of this Dry Run Creek sub-basin in regard to surface water quality, hydrology, hydrogeology, and land use. Historical and present day watershed data were then incorporated into a GIS to develop historic land-use comparison maps.

Groundwater Vulnerability Study

In 2010, a detailed examination of the Devonian aquifer's vulnerability to surface contamination was completed and documented by Gedlinske (2010c) and Gedlinske and May (2011). Information obtained from historical documents, water-well drilling records, and boring logs for monitoring wells installed as part of nearby environmental investigations was combined with GPS mapping of well locations and bedrock exposures into a GIS. The GIS dataset was then used to construct a depth-to-bedrock map of the area (Figure 2). Findings revealed that overlying confining materials present throughout most of the study area were thin to absent in an area east-southeast of UNI's campus, a characteristic indicative of increased aquifer susceptibility to surface contamination.

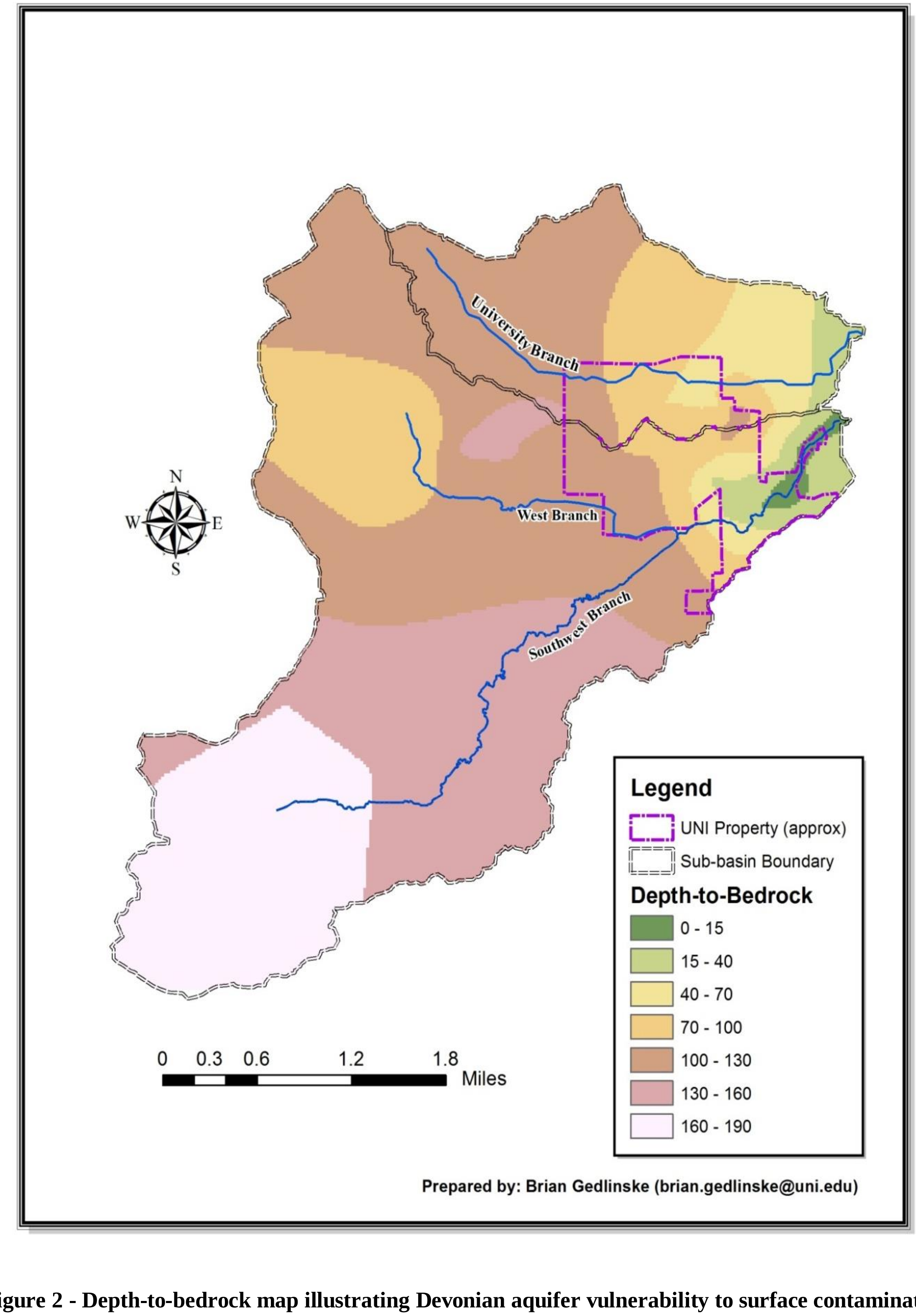


Figure 2 - Depth-to-bedrock map illustrating Devonian aquifer vulnerability to surface contamination - modified from Gedlinske (2010c) and IDNR NRGIS datasets.

USGS Groundwater Flow Study

From 1998 to 2001, the United States Geological Survey (USGS) partnered with Cedar Falls Utilities (CFU) to assess the hydrogeology of the area and model regional groundwater flow patterns for the Devonian aquifer. This study was in response to concerns over the aquifer's vulnerability to contamination from nitrates and organic compounds detected in specific municipal water supply wells (Turco, 2002). From April 1998 to February 1999, bimonthly depth-to-groundwater measurements were collected from a number of existing wells drilled into Devonian and Devonian-Silurian bedrock, including six UNI wells. The USGS-CFU study relied on mean groundwater elevations derived from these measurements to develop a Silurian-Devonian potentiometric surface and to calibrate a groundwater flow-modeling program (i.e., MODFLOW) used to estimate the Devonian aquifer's groundwater flow pattern as an individual hydrogeologic unit.

METHODS OF INVESTIGATION

A variety of primary and secondary data sources were used in completing this study. The following briefly describes information sources, methodologies, and rationale used to investigate and better characterize the spatial and temporal occurrence of PCE in the Devonian aquifer and, to a lesser degree, Dry Run Creek surface water. GIS datasets obtained from the Iowa Department of Natural Resources (IDNR) natural resources geographic information systems (NRGIS) library (available on line at http://www.igsb.uiowa.edu/nrgislibx/) were compiled and integrated into this study to provide a comprehensive depiction of the area's hydrology and hydrogeology.

Existing Groundwater Quality Data

Existing groundwater quality data for the area was obtained by contacting CFU and UNI's Physical Plant Department. Information obtained from CFU consisted of historic PCE analytical data for City Well #5 located just east of UNI's campus (Figure 1). City Well #5 is the only city well in which PCE has been detected. Records obtained from CFU indicate trace amounts of PCE have been present in its groundwater since 1994, the date samples began to be collected and analyzed for a broad range of priority pollutants, including PCE.

National pollutant discharge elimination system (NPDES) permits for UNI's cooling-water discharges came up for renewal in 2010. Presumably, as part of its NPDES renewal efforts, UNI collected wastewater samples from select storm sewer outfalls located across campus during the Fall of 2009. Wastewater discharged to these outfalls consisted of used, non-contact cooling-water from campus wells associated with UNI's Power Plant, the Kamerick Art Building, and Wright Hall-South Maucker Union buildings. These wells are identified as PPL, KAB, and WRT in Figure 1, respectively. Each outfall sample was submitted to Test America in Cedar Falls, Iowa for analysis of metals and a suite of volatile organic compounds (VOC) including PCE.

Potential PCE Point Sources

Potential point sources of PCE were identified by reviewing past Cedar Falls' telephone directories for dry cleaning businesses. Directories, dating back to 1940, were scoured for dry cleaning businesses located within the study area. On-line databases developed by the IDNR and the EPA at https://programs.iowadnr.gov/contaminatedsites/pages/search.aspx and http://www.epa.gov/epahome/commsearch.htm, respectively, were also searched for potential PCE contaminated sites and dry cleaning operations.

Water Sampling

To meet the objectives of the study, water samples were collected from a variety of locations. The following describes the rationale and methodology for cooling-water discharge, groundwater, and surface-water sample collection.

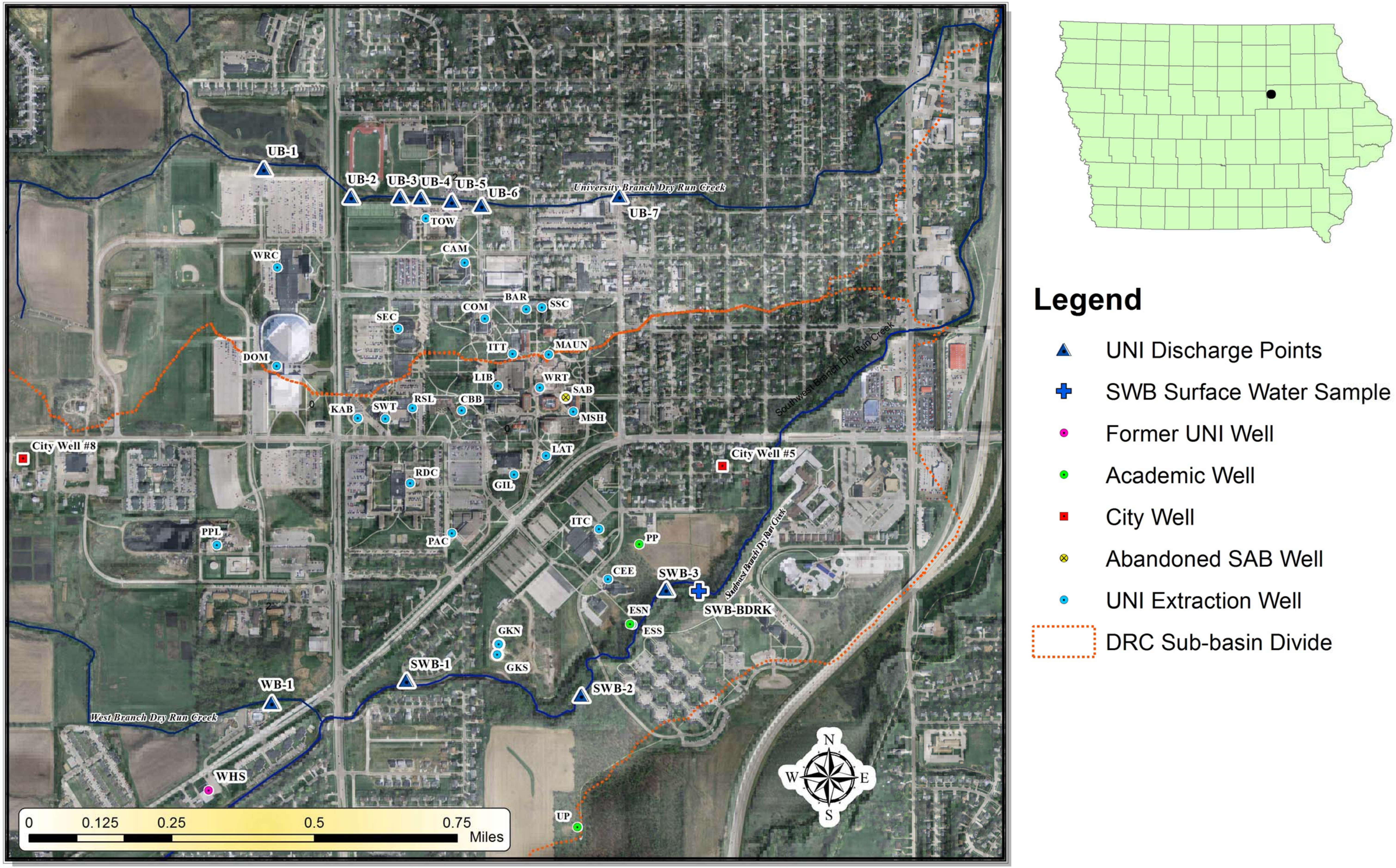
Cooling-water Discharge and Surface Water Sampling. After its use for non-contact cooling, nearly all the groundwater extracted by UNI is discharged to the West, University, and Southwest branch tributaries of Dry Run Creek via storm sewer systems. Roughly 3.5 billion gallons of cooling-water is discharged from the beginning of April through the end of October each year (Gedlinske, 2010a). According to Gedlinske (2010a), cooling-water accounts for a significant portion of streamflow in the University and Southwest branches during this seasonal period. Figure 3 illustrates the location of 11 cooling-water discharge points identified along Dry Run Creek by Gedlinske (2010a). A summary of UNI wells that contribute cooling-water to each Dry Run Creek tributary along with an estimated peak flow rate for each discharge point are provided in Table 1.

Table 1
Dry Run Creek Discharge Rates

Discharge Point ID	Receiving Tributary	Associated Wells	Estimated Peak Cooling-Water Flow Rate (Gallons per minute / Cubic feet per second)
UB-1 through UB-7	University Branch	2, 5-8, 10, 13, 16, 20, 21, 24, 25	8,755 gpm / 19.51 cfs
WB-1	West Branch	9	400 gpm / 0.89 cfs
SWB-1 through SWB-3	Southwest Branch	1, 3, 4, 11, 12, 14, 15, 17-19, 23, 22,	9,190 gpm / 20.48 cfs

On September 26, 2010, water samples were collected from six discharge points. This sampling was performed in an effort to first, determine if used cooling-water conveyed to the University and

Figure 3 - Cooling Water Discharge Points



Southwest branches of Dry Run Creek contained PCE, and second, to indirectly gain groundwater-quality data useful in selecting UNI wells for subsequent sampling.

Surface-water discharge points included in the sampling effort were selected based on 2009 UNI NPDES sampling results and the location of potential PCE point sources. The original intent was to sample five discharge locations along the University Branch (discharge points identified as UB-3 through UB-7 in Figure 3) and two along the Southwest Branch (SWB-2 and SWB-3). However, lack of flow prevented a sample from being collected from SWB-2. This lack of flow was believed to be the result of limited cooling-water needs (and well use) during the weekend of sampling. Campus utility drawings, however, indicate SWB-2 and SWB-3 share much of the same storm water conveyance system and receive cooling-water originating from nearly the same UNI wells. Consequently, it is anticipated that reduced weekend cooling-water discharges were entirely accommodated through discharge point SWB-3.

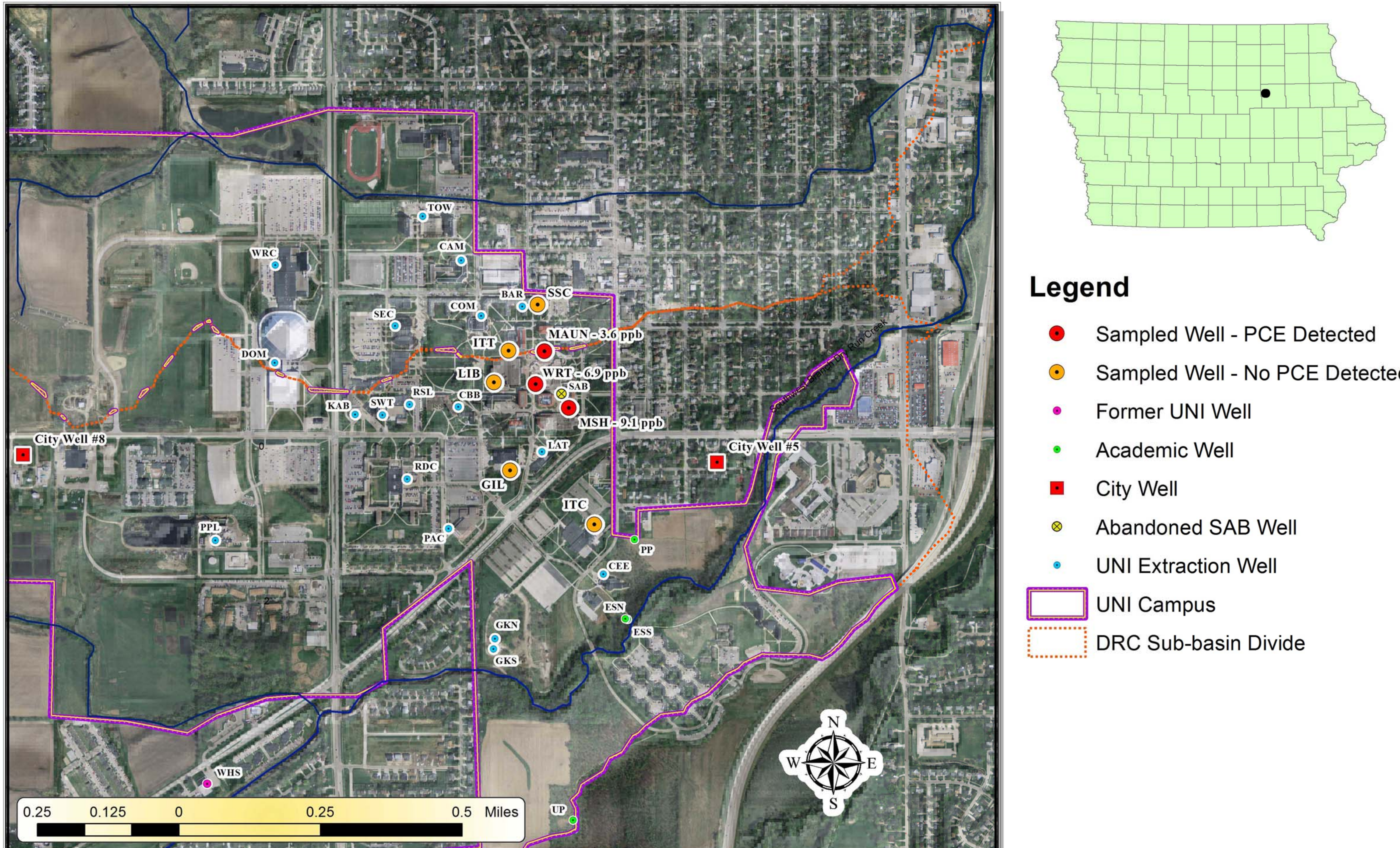
Grab water samples were collected at each of the cooling-water discharge points by filling three 40 milliliter VOC sample vials with water discharged from the storm sewer – surface water outlet. When possible, water samples were collected by filling the vials directly from the storm sewer discharge. However, because of high discharge velocities and outfall characteristics, a number of locations required the use of an unused plastic sampling cup. In these instances, the sampling cup was first rinsed several times with water discharged from the storm sewer before a water sample was collected and carefully transferred into VOC vials.

Each sample vial was labeled with the sampling date, time, location, and sampler’s initials. Immediately after their collection, samples were placed on ice in a cooler for preservation. Additionally, all VOC vials provided by the commercial laboratory contracted for the analytical work were pre-laced with hydrochloric acid (HCl) for sample preservation. Samples were subsequently transported, along with chain-of-custody documentation, to Keystone Laboratories in Newton, Iowa, for PCE analysis using gas chromatography-mass spectroscopy (GC-MS).

Two additional water samples were collected in November 2010 after most of UNI's cooling-water extraction wells were shut down for the season. These included a wastewater (i.e., used cooling-water) sample from SWB-3 and a surface-water sample from the Southwest branch of Dry Run Creek (identified as SWB-BDRK in Figure 3). Unlike most UNI wells, the WRT well operates year round for noncontact cooling needs and discharges to the Southwest branch at SWB-3 (Gedlinske, 2010a). These samples were collected to 1) determine if the WRT groundwater discharged into Dry Run Creek contained PCE; and, if so, to 2) assess the significance of PCE on downstream surface water quality. Freezing temperatures and a lack of recent precipitation provided assurance the SWB-3 sample was undiluted by meltwater or surface runoff entering the storm sewer system. These weather conditions also ensured the SWB-BDRK sample represented baseflow conditions for this Dry Run Creek tributary. As shown in Figure 3, SWB-BDRK was collected a short distance downstream of SWB-3 where exposed bedrock is first found along the stream channel. As the September 2010 sampling results detected PCE in water discharged from SWB-3, the SWB-BDRK sample was collected to determine if detectable concentrations of PCE persist downstream of SWB-3 in an area that appears to represent a direct hydraulic connection between surface water and bedrock comprising the Devonian aquifer.

Groundwater Sampling. The spatial distribution of UNI's groundwater extraction and academic wells relative to City Well #5 is illustrated in Figure 4. Table 2 provides summary information on each campus well in addition to abandoned wells and wells formerly owned by UNI. Groundwater

Figure 4 - Sampled UNI Wells



from eight of UNI's cooling-water extraction wells was sampled on May 20, 2011. These wells are highlighted in Figure 4 and are identified by the campus buildings which use the groundwater for cooling purposes. As shown, the sampled wells included Wright Hall – South Maucker Union (WRT); the Rod Library (LIB); McCollum Science Hall (MSH); Gilchrist (GIL); Maucker Union North (MAUN); Student Services Center (SSC); the Industrial Technology Center (ITC); and the Innovative Teaching and Technology (ITT) center. These wells were selected for sampling based on: 2009 WRT NPDES sampling results; accessibility; laboratory analytical results obtained for the September 26, 2010 surface water discharge sampling event; and their spatial distribution relative to the WRT well, potential PCE point sources, and City Well #5.

Table 2
Study Area Well Summary

UNI Well No.	Associated Building ID	Construction Date	Pumping Rate (gpm)	Bedrock Depth (ft)	Total Depth	IGS Number
1	McCollum Science Hall (MSH)	August 1966	1,600	90	195	18712
2	Commons (COM)	August 1966	370	82	205	18612
3	Gilchrist Hall (GIL)	June 1968	500	55	180	38511 & 20806
4	Maucker Union/Wright Hall (WRT)	August 1968	500	95	195	21058
5	Towers (TOW)	July 1968	685	115 (60W)	191	20805
6	Schindler Education Center (SEC)	December 1971	900	Unknown	200	38512
7	Rod Library (LIB)	May 1974	900	120	222	25058
8	UNI Dome (DOM)	October 1975	1,200	92	200	38513
9	Power Plant (PPL)	August 1980	400	108	200	25942
10	Strayer Wood Theatre (SWT)	February 1976	575	70	210	38514
11	Sabin/Seerley (SAB) ***Abandoned 2009***	April 1982	1,100	87	205	28497
12	Russell Hall (RSL)	January 1982	550	80	210	28499
13	Kamerick Art Building (KAB)	March 1984	1,250	Unknown	210	38515
14	Industrial Technology Center (ITC)	May 1985	650	35	180	27812 & 29886
15	Redeker Dining Center (RDC)	July 1985	750	76	194	38516
16	Student Services Center (SSC)	August 1985	200	120	195	29885
17	Curris Business Building (CBB)	November 1989?	800	83	200	31203
18	Maucker Union Addition (MAUN)	September 1989	640	Unknown	188	38517
19	Latham Hall (LAT)	June 1989	400	61	199	30120
20	Bartlett Hall (BAR)	June 1992	400	107	196	33500
21	Campbell Dining Center (CAM)	June 1992	135	Unknown	Unknown	33501
22	Center for Energy & Environmental Education (CEE)	February 1993	500	36	178	33594
23	Gallagher-Bluedorn Performing Arts Center (PAC)	August 1997? December 1998	1,200	36	200	44476
24	Wellness Recreation Center (WRC)	April 2006	1,700	Unknown	Unknown	Unknown
25	Innovative Teaching and Technology Center (ITT)	August 2005	640	Unknown	180	Unknown
GKN	Groundskeeping North (GKN)	7/28/2010	Unknown	37	120	52638
GKS	Groundskeeping South (GKS)	7/23/2010	Unknown	37	120	52637
5872	Former UNI Warehouse (WHS)	Unknown	85	Unknown	160	38374
UP	Upland Preserve	June 1981	-	80	150	28498
PP	Prairie Preserve	1974?	-	Unknown	Unknown	Unknown
ESN	Earth Science North MW	August 2002	NA	14	80	56441
ESS	Earth Science South MW	August 2002	NA	13	70	56442
City Well #5	City Well #5	May 5, 1961	Unknown	30	145	37618
City Well #8	City Well #8	May 8, 1991	Unknown	100	220	37620

bgs – below ground surface.

A sampling tap in the plumbing from each well was used to obtain a groundwater sample. Before sample collection, the tap valve was opened to purge any stagnant groundwater from the line. Flow was then reduced for sample collection. A set of three 40 milliliter VOC sample vials (with HCl preservative) were then filled with groundwater from each well. Each sample container was labeled with the sampling date, time, location, and sampler's initials. Samples were then packed on ice in a cooler and transported along with chain-of-custody documentation to Keystone Laboratories in Newton, Iowa for GC-MS analysis of PCE.

Geographic Information System (GIS) Development

ESRI GIS software (ArcEditor10) was used to develop a GIS for project analysis and illustration. Information incorporated into the GIS included: UNI well locations; the location of City Well #5 and City Well #8; a depth-to-bedrock GIS dataset developed by Gedlinske (2010c); cooling-water NPDES discharge points to the West, University, and Southwest branches of Dry Run Creek; the SWB-BDRK surface water sampling location; 1998 USGS groundwater measurements; and potential PCE point source locations. 2010 color orthographic photos, 2008 high resolution Light Detection and Ranging (LiDAR) hillshade imagery, LiDAR generated topographic contours, and other pertinent GIS datasets were obtained from the Iowa Geographic Map Server web site (available on line at http://ortho.gis.iastate.edu/), the IDNR's NRGIS library (available on line at http://www.igsb.uiowa.edu/nrgislibx/), and GIS datasets prepared by Gedlinske (2010 a,b,c). A refined groundwater vulnerability map was also developed for the study site by combining a depth-to-bedrock GIS dataset compiled by Gedlinske (2010c) with an IDNR GIS dataset representing the spatial extent of alluvial sand and gravel deposits in the study area.

Groundwater Flow Analysis

While completing the literature review phase of this research project, a number of flaws were found in the 2002 USGS groundwater flow report. Consequently, some raw data that was used to complete the USGS study was retrieved from the USGS National Water Information System (USGS, 2011 - available on-line at http://waterdata.usgs.gov/ia/nwis/gw). This consisted of groundwater level measurements for wells located within the PCE study area. ArcEditor 10 GIS software was then used to interpolate groundwater level measurements and construct groundwater contour maps for the study area.

Groundwater flow within the study area was also assessed through IDNR records for hydrogeological investigations performed at leaking underground storage tank (LUST) sites. Groundwater elevation data, flow maps, and boring logs are integral components of LUST site investigation reports. Unlike the USGS regional groundwater flow study, however, information contained in LUST investigation reports represents more localized, temporal snapshots of groundwater flow for the water-bearing strata screened by investigation monitoring wells. IDNR NRGIS datasets identified 10 LUST investigation sites within the study area, five of which encountered Devonian bedrock during completion of hydrogeological work. Drilling at the remaining LUST sites did not reach bedrock and, consequently, have monitoring well installations screened within unconsolidated deposits overlying the Devonian aquifer.

STUDY FINDINGS AND DATA INTERPRETATION

The following is a summary of study findings. An interpretation of the results is also provided, first by specific topic and then through a more holistic, comprehensive look at study findings.

Groundwater Flow

Regional potentiometric maps developed by the USGS (Turco, 2002) for the Silurian-Devonian aquifer (collectively) and the Devonian aquifer (as a separate aquifer layer) are provided as Figures 5 and 6, respectively. Figure 5 depicts the estimated direction of groundwater flow for the Silurian-Devonian aquifer based on mean groundwater elevation data collected from wells penetrating both Devonian and

Silurian bedrock. Figure 6 represents the modeled groundwater flow direction for the Devonian aquifer as derived from data collected solely from wells completed within Devonian bedrock. As illustrated, both figures indicate the general direction of regional groundwater flow through the study area is to the east and southeast toward the Cedar River.

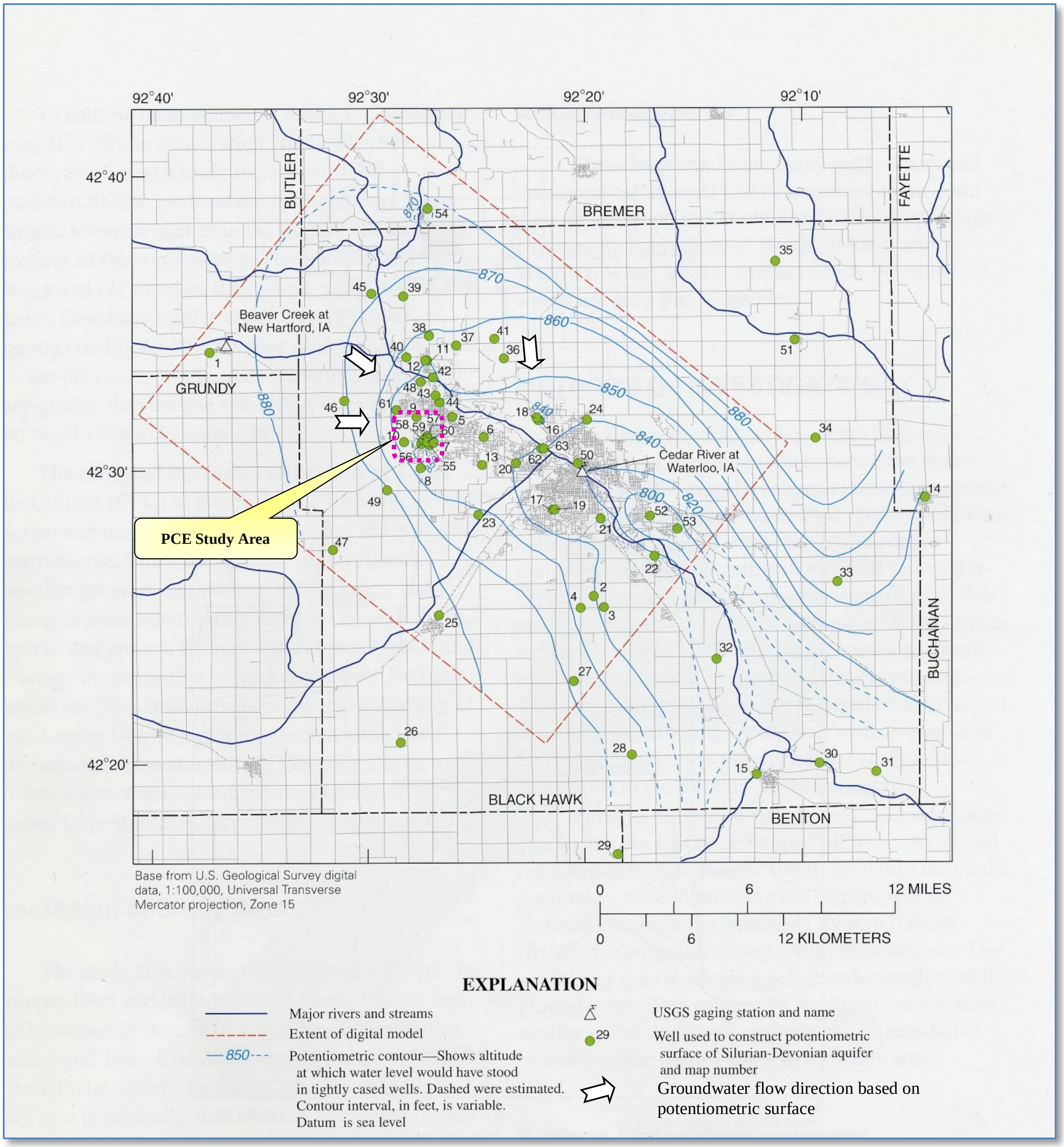


Figure 5 - USGS potentiometric surface constructed from mean measured water levels collected April 1998 to February 1999 for the Silurian-Devonian aquifer (Modified from Turco, 2002, page 4).

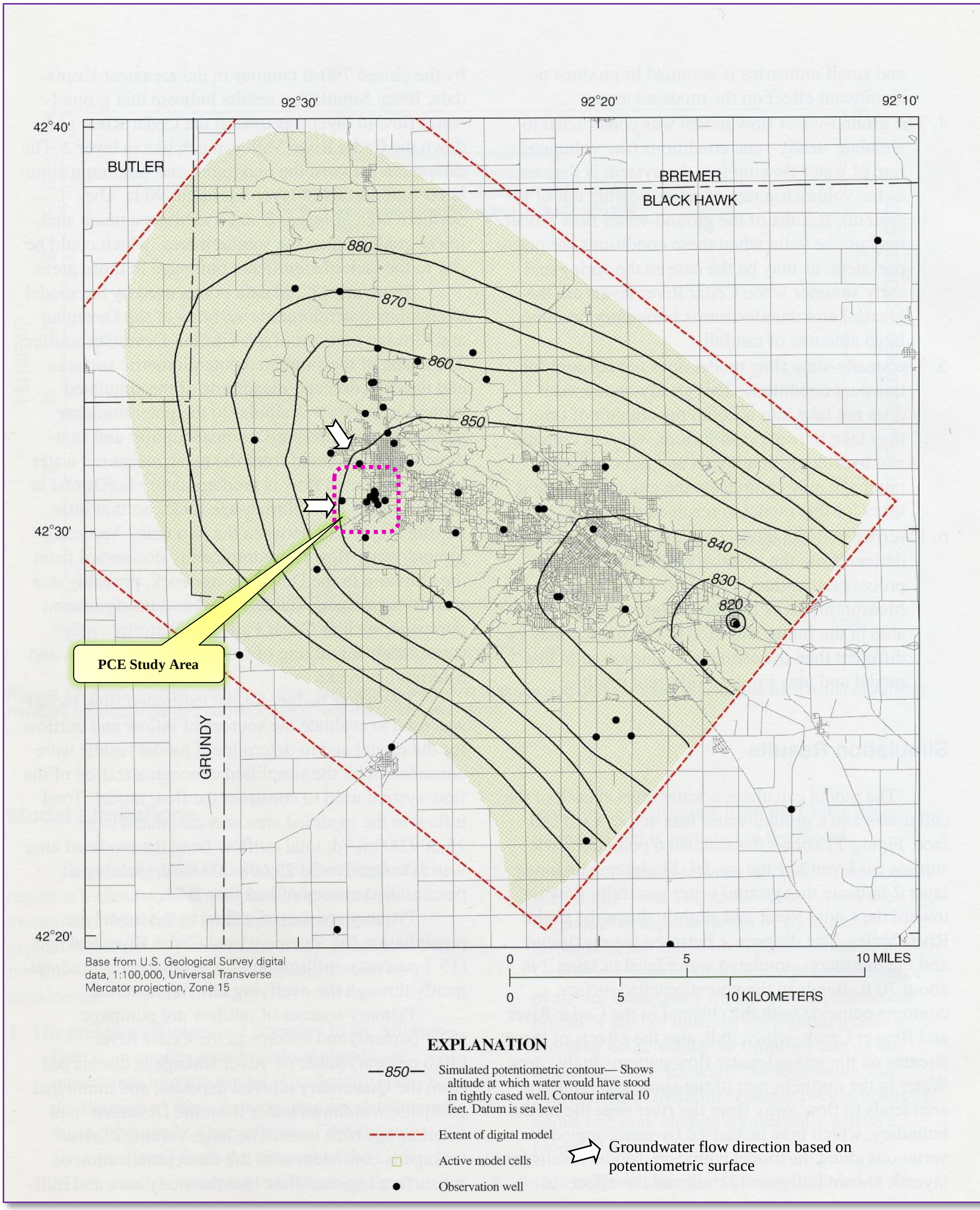


Figure 6 - USGS modeled potentiometric surface for the Devonian aquifer (modified from Turco, 2002, page 24).

Groundwater flow directions obtained from bedrock LUST investigation sites within the study area are summarized in Table 3 and illustrated in Figure 7. As shown, groundwater flow directions at bedrock LUST sites are quite varied and are markedly different from the USGS flow-direction data.

TABLE 3

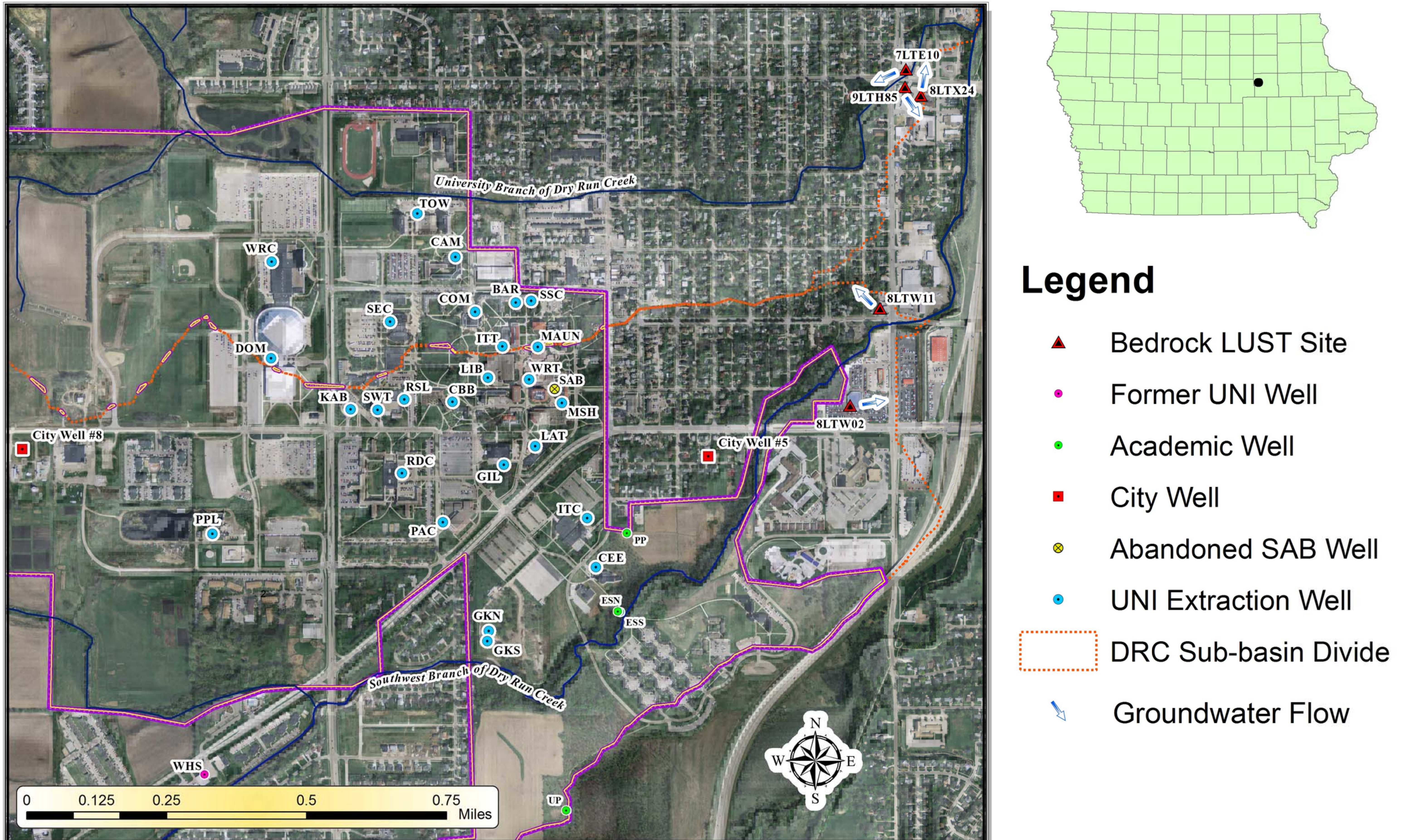
Bedrock LUST Site Groundwater Flow Summary

LUST Site Number	Date of Groundwater Data Collection	Groundwater Flow Direction (approx.)	Site Description
7LTE10	**7/6/2004**	**Southwest**	**1718 Main St. – Cedar Falls Fire Department**
9LTH85	**12/15/1999**	**Southeast**	**1810 Main St. – Formerly Coastal Mart**
8LTX24	**2/10/1994**	**North-Northeast**	**123 E. 18th St. – 18th St. Conoco (formerly P & P)**
8LTW02	**7/14/1993**	**East-Northeast**	**7404 University Ave. - Dan Deery Motor Company**
8TLW11	**11/2/1994**	**Northwest**	**2323 Main St. - Former Petro-N-Provisions**

The scale of the USGS study and LUST reports is very different, as the USGS study covers a much larger area. Consequently, some of the discrepancies between USGS and LUST groundwater-flow directions are a function of scale. However, as indicated previously, flaws in the USGS study are also apparent. Two spatial and temporal factors within the PCE study area were apparently unrealized and, consequently, unaccounted for in the 2002 USGS study. These included the recharge boundary effect provided by Dry Run Creek surface waters and the seasonal operation of UNI wells (Gedlinske, 2010a,b).

Groundwater flow results presented in the 2002 USGS report are based on mean groundwater elevation data determined from bimonthly groundwater level measurements collected from April 1998 through February 1999 (Turco, 2002). As noted by Gedlinske (2010a), a majority of UNI wells operate on a seasonal basis. Wells are typically placed into operation beginning in April and are shut down near the end of October. Figure 8 illustrates the 1998-1999 raw groundwater level data collected from the six UNI wells included in the USGS study (Turco, 2002; USGS, 2011). As shown, each well shows a

Figure 7 - Bedrock LUST Sites - Groundwater Flow Directions



significant drop in groundwater levels during the months in which UNI's wells are placed in operation. Consequently, contrary to conditions described in the 2002 USGS report, groundwater level data for UNI wells included in the USGS study were not representative of static groundwater conditions.

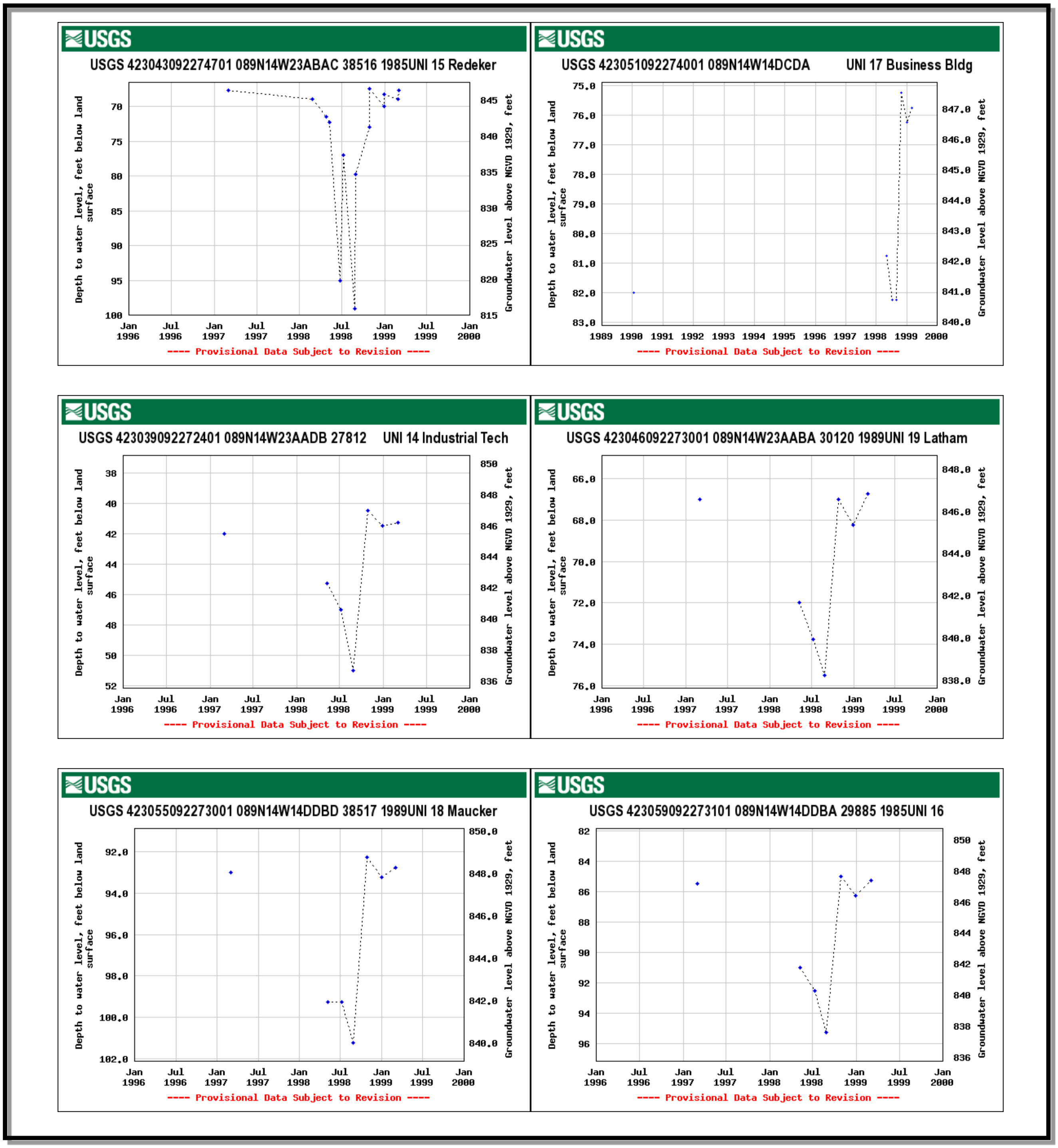


Figure 8 – Plots of raw groundwater level and elevation data used in completing the 2002 USGS study (retrieved from http://waterdata.usgs.gov/ia/nwis/gw) .

Previous studies by Gedlinske (2010a,b) also indicate Dry Run Creek is a losing stream within the study area, particularly where bedrock is shallow or the streambed cuts directly into Devonian bedrock. Consequently, surface waters of Dry Run Creek represent a recharge boundary for the Devonian aquifer, a characteristic that is likely amplified during the seasonal operation of UNI's well field. During UNI's seasonal well use, groundwater withdrawals concurrently depress the potentiometric surface in the well field area while discharging cooling-water to tributaries of Dry Run Creek. This would effectively steepen the groundwater flow gradient between the confined well field area and the Dry Run Creek streambed where the aquifer is unconfined and recharged by streamflow.

Because hydrogeological conditions associated with UNI's seasonal groundwater use and the groundwater recharge effect of Dry Run Creek went unrealized, potentiometric surfaces presented in the 2002 USGS report provide a misleading portrayal of Devonian aquifer groundwater flow within the PCE study area. Groundwater flow directions for bedrock LUST sites, however, appear to better reflect UNI's seasonal well use and recharge from Dry Run Creek. As shown in Figure 7, each bedrock LUST site is located east and northeast of UNI's campus adjacent to Dry Run Creek tributaries. Groundwater flow directions obtained for these sites, particularly those based on groundwater elevation data collected during UNI's seasonal well use, show groundwater moves away from the nearby Dry Run Creek tributary because of streamflow recharge to the aquifer.

Because the 2002 USGS study failed to recognize UNI's pumping effects on the aquifer and the very localized nature of groundwater flow data for bedrock LUST sites, USGS groundwater level data for wells located within the study area were revisited. Water-level measurements obtained by the USGS in August and December of 1998 were subsequently used to develop groundwater contour maps for the PCE study area using Arc Editor 10. These monitoring dates reflect groundwater levels during and following UNI's seasonal well use, respectively. A summary of the groundwater level measurements selected for data analysis is summarized in Table 4.

TABLE 4

1998 USGS Groundwater Level Data

(USGS, 2011 – retrieved from http://waterdata.usgs.gov/ia/nwis/gw)

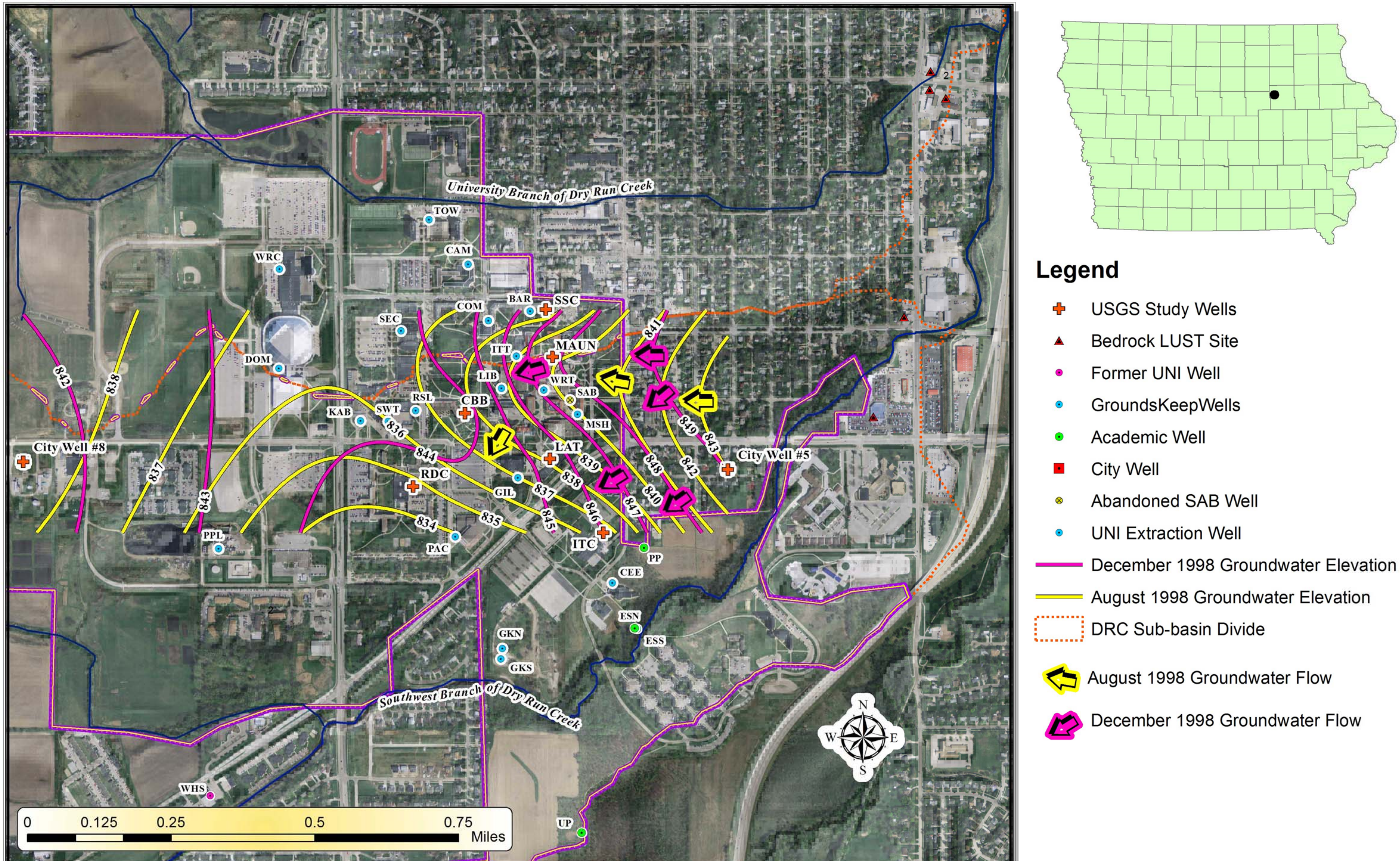
Well I.D.	Date	Land Surface Elevation	Depth-to-groundwater	Groundwater Elevation
LAT	**8/28/98**	**913.63**	**75.5**	**838.13**
LAT	**12/30/1998**	**913.63**	**68.25**	**845.38**
MAUN	**8/28/98**	**941.12**	**101.25**	**839.87**
MAUN	**12/30/1998**	**941.12**	**93.25**	**847.87**
ITC	**8/28/98**	**887.52**	**51**	**853.28**
ITC	**12/30/1998**	**887.52**	**41.5**	**846.02**
CBB	**8/28/98**	**920**[a]	**82.25**	**837.75**
CBB	**12/30/1998**	**920** [a]	**76.25**	**843.75**
SSC	**8/28/98**	**932.72**	**95.25**	**837.47**
SSC	**12/30/1998**	**932.72**	**86.25**	**846.47**
RDC	**8/28/98**	**914.49**	**79.75**	**834.74**
RDC	**12/29/1998**	**914.49**	**70**	**844.49**
City Well #5	**8/25/98**	**877** [a]	**34**	**843**
City Well #5	**12/29/98**	**877**[a]	**28**	**849**
City Well #8	**8/25/98**	**941.59**	**103**	**838.59**
City Well #8	**12/29/98**	**941.59**	**100**	**841.59**

[a] –Indicates ground surface from LiDAR contours used rather than USGS elevation due to discrepancy greater than two feet.

Figure 9 represents groundwater flow maps interpolated for the select USGS data. As shown, groundwater flow patterns are much different from the 2002 USGS study. August 1998 groundwater elevation contours (Figure 9) reflect flow conditions when the UNI's well field is in operation. As indicated by the contours, groundwater flow north of City Well #5 is to the west-northwest toward UNI's main campus area. This flow direction is consistent with the drop in the potentiometric surface that would accompany the operation of UNI's well field during the month of August. Near the western side of UNI's campus area, groundwater flow then begins to swing southwest.

December 1998 groundwater elevation contours shown in Figure 9 reflect flow conditions after UNI's well field had been shut down for approximately two months. Contours indicate groundwater flow

Figure 9 - Groundwater Contours Generated From 1998 USGS Data



following shutdown of UNI's wells shifts to the southwest near City Well #5. The gradient represented by the December 1998 contours is also considerably less in comparison to the August 1998 groundwater contours near City Well #5. As indicated by the groundwater elevations obtained for the two dates, the seasonal operation of UNI's well field creates a significant drop in the potentiometric surface by as much as seven to nine feet.

City Well #5 PCE Sampling Results

Historic PCE analytical data for Well #5 is summarized in Table 5 and graphically illustrated in Figure 10. A graphical plot of detectable PCE occurrences (i.e., analytical data in which PCE was detected at a concentration above analytical quantification limits) along with a trendline is also provided in Figure 10. As shown, PCE concentrations in groundwater from City Well #5 have ranged from less than 0.5 ppb (the analytical quantification limit) to a high of 4.1 ppb on April 28, 2009. Although the coefficient of determination (i.e., the R-squared value) is low, the trendline generated in Figure 10 indicates detectable PCE concentrations are increasing very gradually over time.

Table 5
City Well #5 Historic PCE Monitoring Results
(parts-per-billion)
(J. Lukensmeyer, personal communication, June 15, 2010)

Date	PCE	Date	PCE
2nd quarter/1994	2.0	9/27/2004	ND
2/20/1995	2.1	10/19/2004	ND
4/10/1995	2.7	11/9/2004	ND
7/12/1995	ND	12/9/2004	ND
10/10/1995	ND	1/25/2005	ND
1/15/1996	ND	2/22/2005	2.1
4/17/1996	0.7	3/16/2005	1.2
7/15/1996	ND	4/6/2005	1.4
10/21/1996	ND	5/11/2005	ND
1st Quarter/1997	ND	6/22/2005	ND
2nd Quarter/1997	0.7	10/3/2005	ND
3rd Quarter/ 1997	ND	11/9/2005	ND
4th Quarter/1997	ND	1/17/2006	0.6
2/18/1998	1.5	2/22/2006	2.1
3/10/1998	0.8	3/6/2006	1.6
4/14/1998	1.7	4/17/2006	0.8
5/21/1998	ND	5/10/2006	ND
2/5/1999	1.9	6/15/2005	ND
3/22/1999	1.6	11/7/2005	ND
4/12/1999	1.6	12/9/2006	ND
5/11/1999	ND	1/11/2007	1.0
1/24/2000	1.4	2/22/2007	2.4
2/7/2000	2.2	3/20/2007	3.2
3/21/2000	2.9	4/19/2007	0.5
4/5/2000	3.0	5/10/2007	ND
6/6/2000	ND	6/15/2007	ND
7/24/2000	ND	7/16/2007	ND
1/17/2001	1.2	8/21/2007	ND
2/14/2001	1.3	9/13/2007	ND
3/14/2001	1.3	11/13/2007	ND
4/10/2001	0.8	12/12/2007	ND
5/14/2001	ND	2/21/2008	1.2
1/30/2002	ND	3/13/2008	2.4
2/11/2002	ND	5/14/2008	2.0
3/11/2002	0.7	7/7/2008	ND
4/8/2002	1.7	9/10/2008	ND
5/7/2002	ND	10/19/2008	ND
1/8/2003	0.8	12/16/2008	ND
2/25/2003	2.0	1/16/2009	1.8
3/24/2003	1.6	2/5/2009	2.3
4/28/2003	ND	3/12/2009	3.6
5/19/2003	ND	4/28/2009	4.1
12/2/2003	ND	5/21/2009	1.9
1/9/2004	0.9	6/10/2009	ND
2/11/2004	1.3	4/1/2010	2.7
3/8/2004	0.7	4/21/2010	1.6
4/6/2004	0.6	5/18/2010	0.6
5/5/2004	ND		

ND – Indicates not detected at a quantitation limit of 0.5 ppb

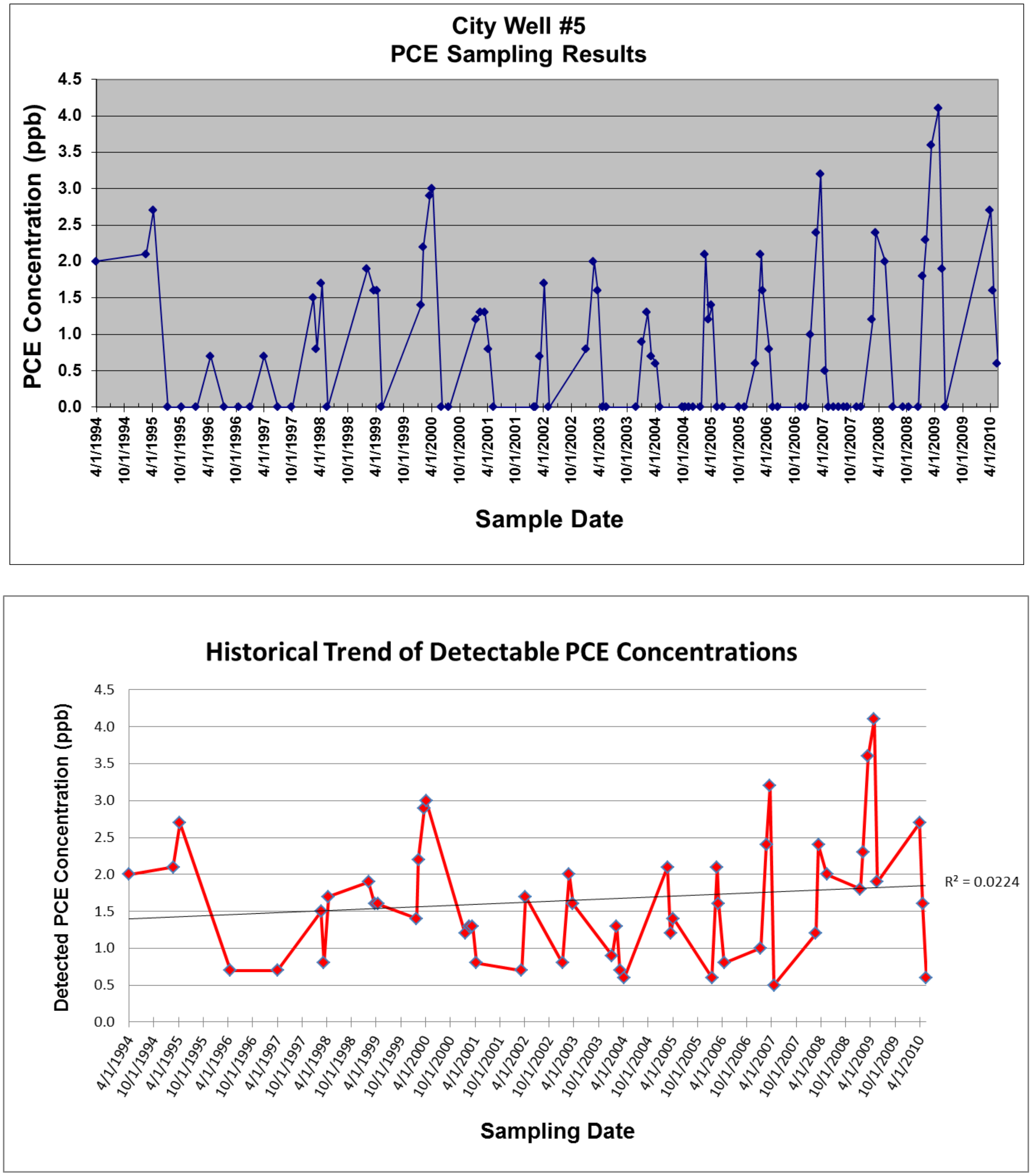


Figure 10 – Historic PCE data (top) and trend of detectable PCE concentrations (bottom) for City Well #5.

It's also apparent from historic sampling data that a temporal pattern exists for City Well #5 PCE detections. As shown in Figure 10 and Table 5, PCE is only detected during sampling events conducted within the first four to five calendar months of the year. No PCE is detected in groundwater for later sampling events (typically after the month of May).

The temporal PCE detection pattern reflected in Figure 10 correlates quite well with the seasonal operation of UNI's groundwater extraction wells. MSH is one of UNI's most heavily used wells and is located approximately 1,500 feet northwest of City Well #5. According to Gedlinske (2010a), MSH groundwater withdrawals account for roughly 11 percent of UNI's total annual groundwater usage. It is also the second most productive well on campus, yielding 1,600 gallons-per-minute (gpm). Figure 11 graphically illustrates the 2007 and 2008 PCE analytical results for City Well #5 as compared to monthly groundwater withdrawals for MSH during that same period. As shown, a temporal correlation clearly exists between MSH's seasonal groundwater use and PCE groundwater detections for City Well #5. This data indicates the seasonal use of UNI's wells, particularly with respect to MSH, exerts a hydraulic influence over the PCE groundwater plume, effectively drawing it away from City Well #5. Groundwater flow contours developed from select USGS groundwater level measurements (see Figure 9) also supports this correlation.

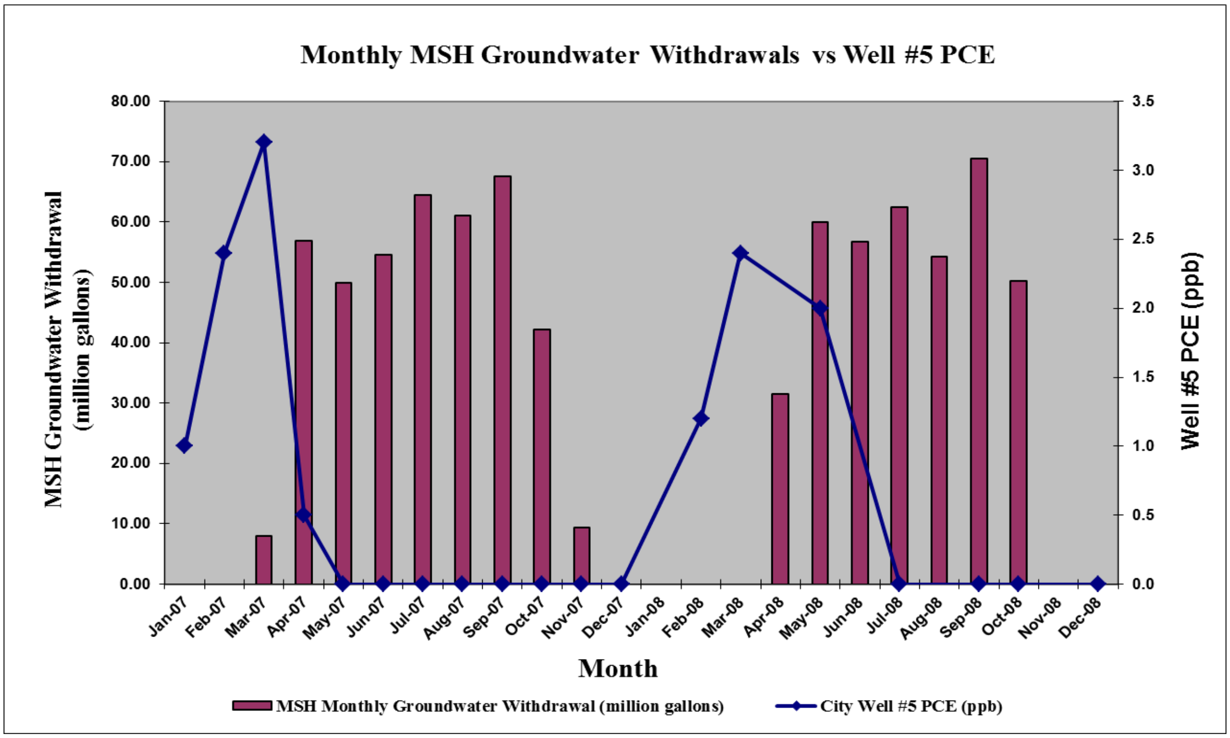


Figure 11 – Temporal comparison of City Well #5 PCE detections and monthly groundwater withdrawals from McCollum Science Hall (MSH).

UNI NPDES Outfall Sampling

PCE analytical results obtained as part of UNI's effort in 2009 to renew its NPDES permit are provided in Table 6. Table 6 also identifies the cooling-water source well for each outfall. As indicated, PCE was detected in cooling-water discharged to outfall NPDES 008 on two separate sampling occasions at concentrations of 8.39 and 4.76 ppb, respectively. This outfall location represents groundwater withdrawn from WRT. No PCE was detected in wastewater discharged to NPDES 013 and NPDES 017, indicating the KAB and PPL wells lie outside of the extent of the PCE plume.

TABLE 6

2009 UNI Storm Sewer Outfall Sampling - PCE Results

Outfall Number	Sampling Date	PCE Concentration (ppb)	Associated UNI Well ID
NPDES 008	**10/28/09**	**8.39**	**Wright Hall – South Maucker Union (WRT)**
NPDES 008	**11/23/09**	**4.76**	**Wright Hall – South Maucker Union (WRT)**
NPDES 013	**10/27/09**	**<1.00**	**Power Plant (PPL)**
NPDES 017	**10/28/09**	**<1.00**	**Kamerick Art Building (KAB)**

Cooling-Water Discharge Points and Surface Water Sampling

Laboratory analytical results for cooling-water discharge samples collected along the University and Southwest branches of Dry Run Creek are summarized in Table 7. It also includes laboratory results obtained for surface water sample SWB-BDRK collected downstream of SWB-3 in November 2010. As shown, water collected from SWB-3 during the September 2010 and November 2010 sampling events contained PCE at 3.8 and 2.2 ppb, respectively. PCE was not detected in any other cooling-water discharge samples or in surface water sample SWB-BDRK.

According to UNI utility drawings, campus wells that contribute cooling-water to SWB-3 during UNI's campus building cooling season include WRT, MSH, GIL, MAUN, LAT, ITC and CEE. Flow from these wells is represented by the September 2010 SWB-3 sampling results. However, in late Fall, all wells except WRT are shut down. Consequently, the November 2010 SWB-3 sample represents WRT cooling-water discharge only.

TABLE 7

2010 Dry Run Creek Cooling-Water Discharge and Surface Water Sampling Results

Sampling Location	Sample Date	PCE Concentration (ppb)	Description
UB-3	9/26/10	<1.0	Cooling-water discharge to the University Branch near northeast corner of UNI tennis courts
UB-4	9/26/10	<1.0	Cooling-water discharge to the University Branch just west of pedestrian bridge located north of Bender Hall
UB-5	9/26/10	<1.0	Cooling-water discharge to the University Branch just North of Dancer Hall
UB-6	9/26/10	<1.0	Cooling-water discharge to the University Branch beneath Campus Street Bridge
UB-7	9/26/10	<1.0	Cooling-water discharge to the University Branch beneath College Street Bridge
SWB-3	9/26/10	3.8	Cooling-water discharge to the Southwest Branch southeast of CEEE Building
SWB-3	11/10/10	2.2	Cooling-water discharge to the Southwest Branch southeast of CEEE Building
SWB-BDRK	11/10/10	<1.0	Downstream of SWB-3 at first visible bedrock exposure along stream bank

As indicated, the September 2010 SWB-3 sample was slightly higher in PCE than the November 2010 sample, suggesting other wells (in addition to WRT) discharge PCE-laden water to SWB-3, or the PCE concentration in WRT groundwater was higher in September. PCE concentrations detected on each sampling date, however, were less than the PCE concentration detected for both NPDES 008 outfall samples collected by UNI in 2009. Although the PCE concentration in the September 2010 SWB-3 sample may have been the result of dilution from other wells, the November 2010 SWB-3 PCE concentration suggests a limited degree of contaminant attenuation may be taking place as discharged cooling-water travels through the storm sewer to SWB-3. As PCE has a greater affinity for air than water, air stripping is often used as an effective treatment for PCE tainted groundwater. It’s possible that turbulent flow within the storm sewer may cause some PCE to be stripped away before discharge at SWB-3.

Analytical results for surface water sample SWB-BDRK indicate the presence of PCE within the Southwest branch of Dry Run Creek is short-lived downstream of SWB-3. However, since SWB-

BDRK was collected when SWB-3 discharge consisted solely of WRT groundwater, additional sampling would be needed to determine if this holds true during UNI's well operating season when numerous wells are discharging water to SWB-2 and SWB-3.

UNI Groundwater Sampling Results

PCE analytical results for the eight groundwater samples collected May 20, 2011, are presented in Table 8. As shown, groundwater from WRT, MAUN, and MSH contained PCE at concentrations of 6.9, 3.6, and 9.1 ppb, respectively. These results are consistent with the cooling-water discharge sampling results obtained for SWB-3 in 2010. PCE was not detected at or above the analytical reporting limit of 1 ppb in the remaining five wells.

TABLE 8

May 20, 2011 UNI Well Sampling Results

Sampling Location	Sample Date	PCE Concentration (ppb)	Description
WRT-1	5/20/11	6.9	Wright Hall – South Maucker Union Well
LIB-1	5/20/11	<1.0	Rod Library Well
MSH-1	5/20/11	9.1	McCollum Science Hall Well
GIL-1	5/20/11	<1.0	Gilchrist Hall
MAUN-1	5/20/11	3.6	Maucker Union North Well
SSC-1	5/20/11	<1.0	Student Services Center Well
ITT-1	5/20/11	<1.0	Innovative Teaching Technology Center Well
ITC-1	5/20/11	<1.0	Industrial Technology Center Well

Potential PCE Point Sources

A review of past telephone directories for Cedar Falls, an IDNR contaminated sites database, and EPA records identified several potential PCE point sources within the study area. These include five former dry cleaning locations and one former manufacturing site. A summary description of each potential PCE source site is provided in Table 9 and their locations are illustrated in Figure 12. As shown, four former dry cleaning businesses were once located just northeast of UNI's campus within the College Hill area of Cedar Falls. These sites, identified as DC-1 through DC-4, are situated north and topographically downgradient of the University and Southwest branch sub-basin divide. DC-5 is a former dry cleaning facility located along Main Street within Dry Run Creek's Southwest branch sub-basin. Additionally, IDNR records reveal PCE soil contamination was discovered at a former manufacturing site (identified as MFG-1) during utility excavation work performed in the southwest portion of the property.

TABLE 9

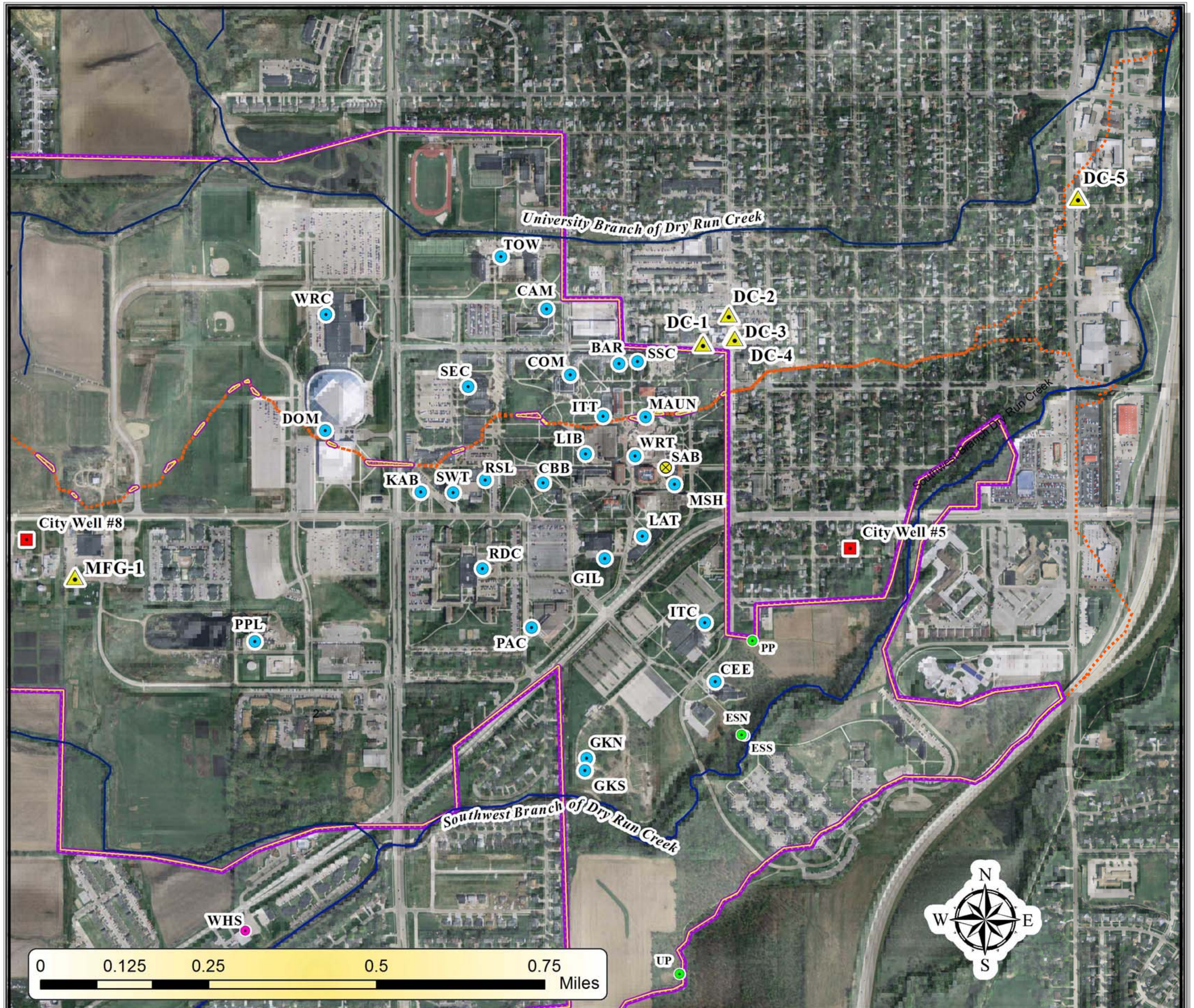
Potential PCE Point Sources

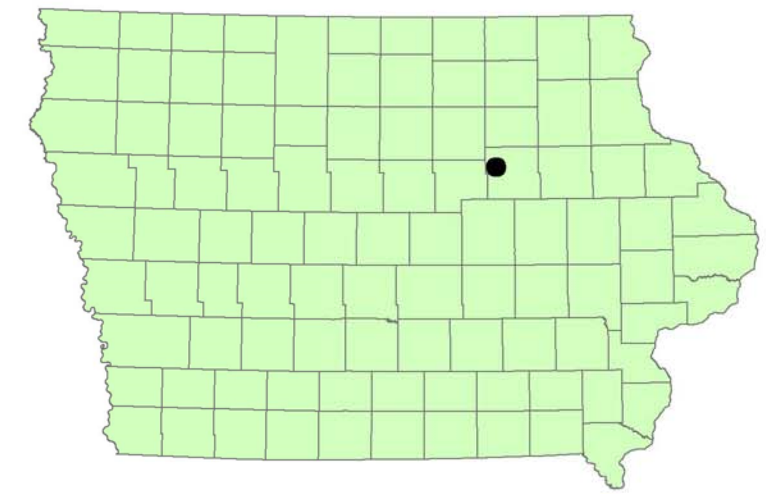
Site ID	Former Operation	Street Address	Former Name(s)	Est. Period of Operation
DC-1	**Dry Cleaning**	**917 West 23rd Street**	**Campus Cleaners/Fashion Cleaners**	**1945-1982**
DC-2	**Dry Cleaning**	**2209 College Street**	**Triangle Cleaners**	**1950-1970**
DC-3	**Dry Cleaning**	**2223 College Street**	**Six Hour Cleaners**	**1968-1975**
DC-4	**Dry Cleaning**	**2226 College Street**	**Wonder Cleaners**	**1945-1950**
DC-5	**Dry Cleaning**	**1934 Main Street**	**Dodge Service Quick Cleaners/Serve Quik One Hour Cleaners**	**1975-2007**
MFG-1	**Manufacturing**	**2412 West 27th Street**	**Wayne Engineering**	**1970-1996**

Devonian Aquifer Vulnerability

Figure 13 illustrates an aquifer vulnerability map developed for the study area. It depicts the depth to the Devonian bedrock aquifer as interpolated by Gedlinske (2010c) overlain by an IDNR-NRGIS dataset depicting the estimated spatial extent of alluvial deposits. Areas most susceptible to near-surface

Figure 12 - Potential PCE Source Areas





Legend

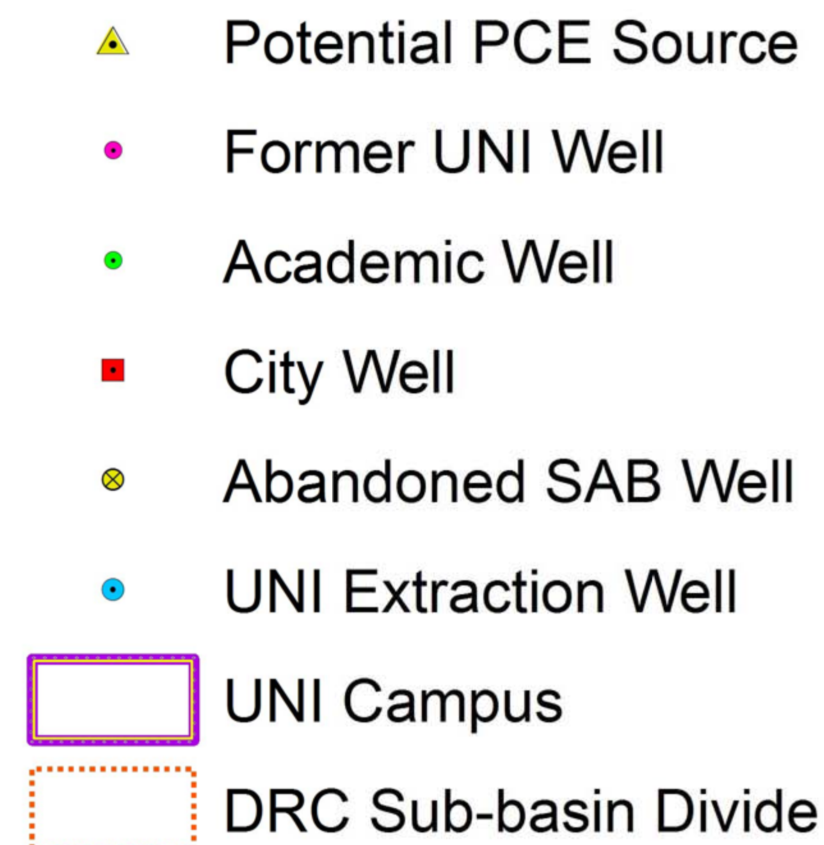
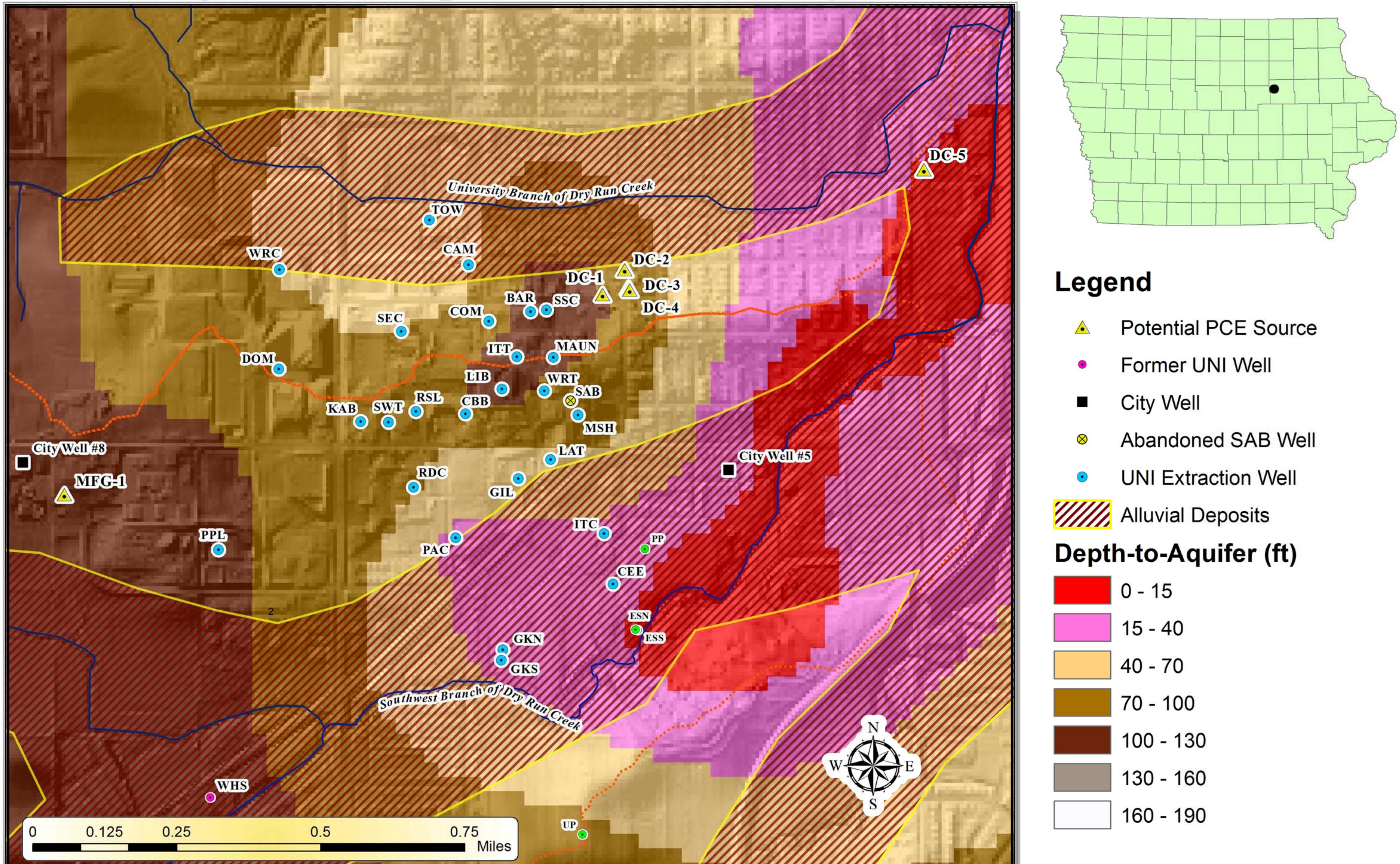


Figure 13 - Aquifer Vulnerability



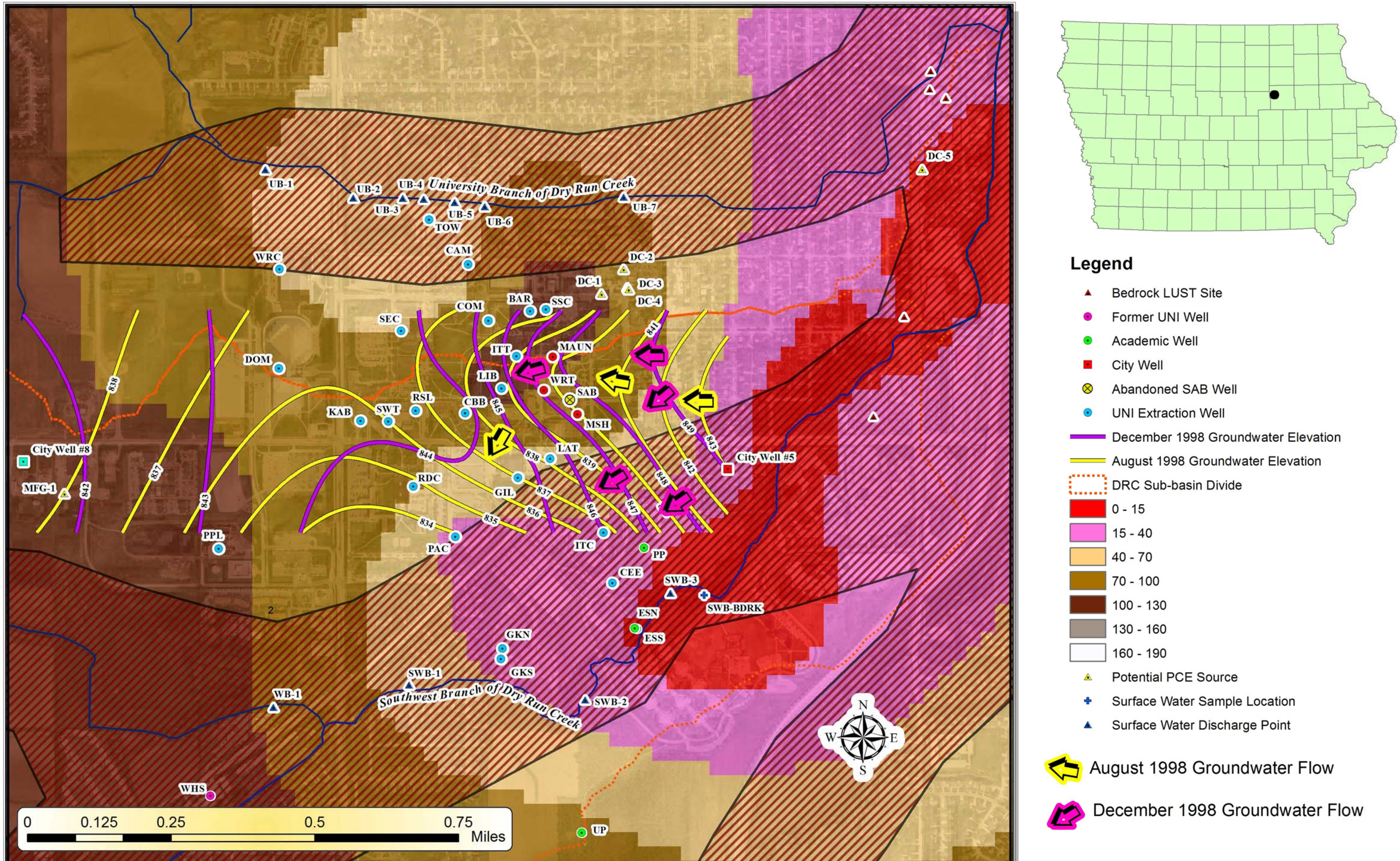
contamination are represented by zones where: 1) alluvial deposits overly shallow bedrock; or 2) where the Dry Run Creek stream channel cuts directly into Devonian bedrock, providing a direct hydraulic connection between surface water and the Devonian aquifer. Contaminant transport in these areas would be relatively unimpeded due to thin or absent confining strata, a short and direct travel pathway to the aquifer, and the low contaminant attenuation - high permeability characteristics associated with coarse-grained alluvial deposits and highly fractured carbonate bedrock.

Comprehensive Spatial Observations

Figure 14 illustrates the aquifer vulnerability map developed for the study area combined with locations of known potential PCE point sources; groundwater flow direction estimates based on select 1998 USGS data; and an estimated extent of the PCE plume from groundwater sampling data. Cooling-water discharge points and surface-water sampling location SWB-BDRK are also included. The following is a comprehensive discussion of findings in regard to the extent and temporal characteristics of the PCE plume relative to potential PCE point sources, areas of high aquifer susceptibility, and groundwater flow.

Extent of PCE Plume, Groundwater Flow, Aquifer Susceptibility, and Potential Point Sources. As shown in Figure 14, the west and southwest extent of the PCE plume appears to be fairly well defined by analytical results for the May 20, 2011 groundwater sampling event. Laboratory results indicate the PCE plume extends beneath several east campus buildings including the Maucker Union, McCollum Science Hall, Sabin Hall, Seerly Hall, Wright Hall, and possibly portions of Lang Hall, Latham Hall, the Biology Research Complex, and the Rod Library. Laboratory results also indicate groundwater PCE concentrations increase to the east-southeast of Maucker Union and that groundwater from WRT and

Figure 14 - Comprehensive Findings for PCE Study Site



MSH exceeds the drinking water MCL for PCE (5 ppb). City Well #5 appears to delineate the southern edge of the plume.

The extent of the plume east and northeast of UNI's campus is unknown due to a lack of bedrock wells for groundwater sampling. Although sampling of select LUST bedrock monitoring wells in the eastern portion of the study area may provide better definition on the spatial extent of the PCE plume, it's likely that additional Devonian aquifer well installations will be needed, particularly for source identification.

As illustrated in Figure 14, only one known potential PCE point source, DC-5 (the former Dodge Cleaners site at 1934 Main Street), lies within a zone where the Devonian aquifer is highly vulnerable to surface contamination. At this location, permeable alluvial deposits overlie shallow bedrock. Other known potential sources identified within the study area are situated outside the estimated extent of alluvial deposits in upland areas where an estimated 70 to 130 feet of loess and glacial till overly the aquifer (Gedlinske, 2010c). These thick, clay-rich deposits should provide a protective confining layer for the Devonian aquifer. Additionally, the former manufacturing site with known PCE soil contamination (MFG-1) is located over a mile away from the PCE plume. Based on hydrogeological characteristics associated with each potential PCE point source, their spatial distribution relative to the PCE plume, and groundwater flow patterns generated from some 1998 USGS groundwater elevation data (Figure 9), DC-5 appears most suspect.

It's important to note, however, that the cluster of former dry cleaning establishments located just northeast of UNI's campus (DC-1 through DC-4) cannot be excluded as sources of the PCE detected in the aquifer. Sanitary sewer lines tend to parallel surface drainage, taking advantage of gravity flow whenever possible. As sanitary sewers were once a common means of PCE waste disposal, a leaky sewer line, possibly interacting with thin, discontinuous lenses of coarse-grained deposits, could have provided a more indirect pathway to the Devonian aquifer. Although more complex, this pathway may have allowed PCE to migrate laterally and topographically downgradient of these former dry cleaning sites until PCE reached more vulnerable groundwater zones to the northeast.

Analysis of some 1998 USGS groundwater data produced groundwater flow patterns completely different from those developed in the 2002 USGS study. Results, however, are consistent with the recharge effect from Dry Run Creek streamflow, seasonal groundwater flow effects caused by the operation of UNI's well field, and the temporal detection of PCE at City Well #5. As illustrated in Figures 9 and 14, groundwater flow north of City Well #5 is primarily to the southwest during periods when UNI's well field is largely inactive. However, during operation of UNI's well field, the potentiometric surface drops considerably causing groundwater flow north of City Well #5 to shift to a west-northwest direction. Based on temporal PCE detection patterns for City Well #5, this shift in groundwater flow direction apparently diverts the PCE plume away from City Well #5 toward UNI's campus. In short, UNI's seasonal groundwater use provides a degree of hydraulic protection for City Well #5.

Groundwater flow patterns illustrated in Figures 9 and 14 insinuate the PCE plume originates somewhere northeast of City Well #5, again implicating DC-5 as a likely source area. These patterns also indicate the leading edge of the PCE plume during periods when UNI's well field is inactive is in the vicinity of City Well #5. Once UNI's well field becomes active, however, the plume's leading edge is re-directed to the west-northwest toward UNI's campus.

Surface Water Quality Impact on Dry Run Creek. Although UNI's seasonal well use provides hydraulic protection for City Well #5, PCE laden groundwater withdrawn from a number of UNI wells is discharged to the Southwest branch of Dry Run Creek through discharge points SWB-2 and SWB-3. Limited sampling data, however, indicates the concentration of PCE in cooling-water discharged to this tributary is diluted or attenuated to a level below the EPA MCL of 5 ppb. Once PCE enters streamflow, the detectable presence of PCE appears to be short lived.

CONCLUSIONS

The findings provide key information on the extent of the PCE plume, aquifer vulnerability, groundwater flow, and potential PCE point sources. However, as indicated below, numerous gaps in data availability remain. The following highlights main conclusions gained from this study. Also provided are recommendations for additional work aimed at better characterizing the PCE plume and hydrogeological characteristics of the area.

- Expanded groundwater sampling better defines the extent of the PCE plume, particularly its west, northwest, and southern extent. However, the extent of the PCE plume to the area east and northeast of UNI's campus cannot be determined due to a lack of bedrock wells for groundwater sample collection. Although groundwater samples from wells used to monitor bedrock LUST sites may provide additional information on the northeastern extent of the PCE plume, spatial gaps in the data will likely remain in key areas without the installation of additional sampling wells.
- The spatial distribution of potential PCE point sources relative to the aquifer susceptibility map developed for the study area indicates the former dry cleaning facility DC-5 is located in a highly vulnerable area. As indicated by GIS data analysis, DC-5 is located in an area where permeable alluvial deposits overlie shallow bedrock. Other potential PCE point sources identified during this study were located in areas where the Devonian aquifer is confined by thick deposits of clay-rich loess and till.
- The groundwater flow directions from the 2002 USGS study are misleading within the PCE study area. I attribute this to generalizations created by scale issues, unrealized consequences of UNI's

seasonal well use, and the recharge boundary created by the tributaries to Dry Run Creek in areas where the Devonian aquifer is unconfined. Although groundwater-flow data available for bedrock LUST sites appeared to better reflect the recharge boundary effect of Dry Run Creek surface waters, the data are too localized to be of much further value. Additionally, groundwater flow data for each LUST site was determined at different dates, subjecting it to temporal variations that undoubtedly occur and prevent its collective use to depict groundwater flow.

Analysis of some water-level data for wells monitored as part of the 2002 USGS study appears to offer the most representative and consistent portrayal of groundwater-flow patterns within the PCE study area. Contours of groundwater elevations generated from this data display flow patterns that are consistent with the temporal detection of PCE in City Well #5, UNI's seasonal groundwater use, and the recharge boundary represented by the surface waters of Dry Run Creek. Based on USGS groundwater-level data collected from wells located within the PCE study area, groundwater flows to the southwest during periods when UNI's well field is inactive. Once UNI's seasonal groundwater use begins, groundwater flow shifts to a west-northwest direction toward UNI's campus.

- Seasonal groundwater withdrawal patterns by UNI and groundwater flow directions interpolated from select raw USGS data correlates well with the historic temporal pattern of PCE detections in groundwater from City Well #5. During periods when UNI's well field is inactive, PCE plume migration (and groundwater flow) is largely to the southwest towards City Well #5. Once UNI's well field is placed in operation, however, the groundwater flow direction shifts to the west-northwest toward UNI's campus. Findings indicate the operation of UNI's well field exerts an hydraulic influence over the PCE plume, effectively drawing it away from City Well #5.

- Although cooling-water discharged by UNI into Dry Run Creek accounts for a significant portion of streamflow in the University and Southwest branch tributaries, PCE was only detected in cooling-water discharged to the Southwest branch. Surface water sampling results, however, suggest PCE is quickly diluted to non-detectable levels within a short distance downstream from cooling-water discharge points. Additional surface water sampling may be warranted to determine if this observation holds true during the height of UNI's groundwater use and cooling-water discharge to the Southwest branch of Dry Run Creek.

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